

# **Effect of Process Modeling on Product Quality of Superalloy Forgings**

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## **Abstract**

Even so effects of forming, heating and cooling on microstructure and therefore mechanical properties are well understood for superalloys like alloy 718 the influence of complex multistep thermomechanical processes can not be described analytically. Thus the usage of simulation tools is a necessity in order to secure stable processes and resulting properties. With increasing computer power and the development of the finite element method it is today possible to simulate these processes with high accuracy in a sufficient time period. Typical simulation results like optimization of material input, a guaranteed die filling as well as prevention of folding or overheating will be part of the paper. In addition the benefits of recent developments on residual stress and distortion simulation as well as microstructure and nanostructure models and their influences on mechanical properties will be discussed.

Finally some simulation examples including process variations and their effects on the quality of parts will be compared with results of microstructure evaluation and mechanical testing of forgings.

Using these simulation approaches linked with recent developments on fatigue modeling, it is possible to obtain minimized weight and maximized lifetime in the final part and therefore optimize the total life cycle costs.

## **Introduction**

The driving force to use modeling and simulation in order to increase the certainty of a process is interrelated with the risk regarding undesired process deviation. Therefore centuries prior to the development of computers scaled physical models have been used especially in architecture to reduce the risk of collapsing buildings (Figure 1). The reason for the development of simulation in forming processes is similar: With increasing process costs, more expensive materials and therefore higher costs due to a nonconforming or failed forging (for instance to coarse microstructure in an engine disc) the importance of reducing the risk grows higher. Therefore in the early days plasticine models have been used to show grain flow and to get an idea about die filling (Figure 2), even so the material behavior is pretty different compared to superalloys for instance.



Figure 1: String model of the supporting structure of a church tower used to design tension free structures by the famous architect Antonio Gaudi and view inside a tower of the Sacrada Familia.

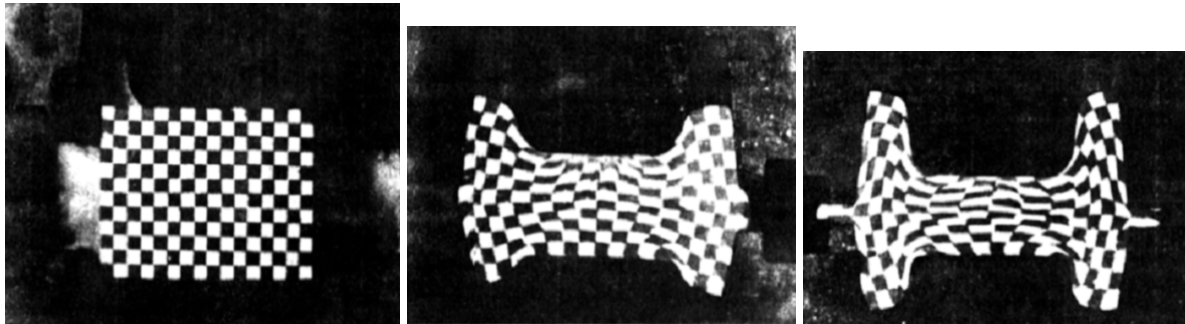


Figure 2: Easy grain flow model of a die forming process using plasticine in different colors [1].

Later on some analytical models e.g. [2] as well as the slab method e.g. [3] were used to predict forming loads and strains. These methods did not find their way from basic research to industrial use at that time, due to their high effort of problem dependent customization. These insufficiencies could be overcome with the development of the finite element method [4, 5] and the increase of computer power in the 1970's and 1980's. Finally customer friendly software designed for special purposes, e.g. for massive deformation, paved the way for industrialization of the finite element method (FEM).

At Bohler Schmiedetechnik GmbH & Co KG the decision to use finite element (FE) simulation in order to model die forging processes was made with the ambition to forge parts for aircraft engines in 1993. Since that time all forging processes for critical parts for aircraft industry as well as for power plants are designed using the special purpose software DEFORM™. In the following the main influences on the quality of simulation results and consequently on the quality of the forged part are discussed.

## Finite Element Simulation of Thermomechanical Processes

Simulation in an industrial environment like the forging industry is mainly influenced by three driving forces:

Time	Process development and therefore simulation should be as fast as possible.
Cost	The developed process and the simulation process itself should be as cheap as possible.
Quality	The developed process should guarantee a high quality final product.

Thus, the main challenge is to find the right balance between those driving forces in dependence of the problem, which has to be modeled. Due to the bad forgeability of superalloys and the very high costs of forging trials the main driving force for process development is obviously the quality of the final part. Therefore higher efforts can be made with regard to cost and time for the development.

Some apparent possibilities that influence the quality of simulation output are part of the finite element method. The accuracy can be easily altered by the amount of finite elements used to describe the geometric shape and to approximate the continuum behavior. The limits of this approach are set by the time for simulation, which is proportional to the amount of elements, and the available memory to solve the sets of partial differential equations. The possibility of a variable mesh density, which is implemented in most of the modern finite element codes, is an elegant method to slightly overcome these limits. The accuracy of the numerical solution is also strongly dependent on the size of the simulation steps (time, stroke, etc.). For nonlinear physical problems like plastic deformation the methods of linearization of the set of nonlinear equations and the method to solve this set also affects convergence and simulation time. In most FE codes the user can choose these methods suitable for the problem, which has to be solved (e.g. for complex geometry 3D simulations of hot die forging Newton-Raphson linearization is used to develop the system of linear equations and most likely the iterative conjugate residual method is used to solve this equations efficiently [6]). Considerable benefit with regard to calculation time and quality of forming simulations can be achieved by efficient automatic remeshing, which helps preventing massive distortion of the finite element mesh and therefore convergence problems.

Beside these influence parameters more or less given by the system, the biggest impact on the quality of simulation output comes from the material data. Dependent on the problem, which has to be solved, physical parameters for elastic, plastic and thermal material behavior as well as properties of interfaces and boundaries have to be fed into the simulation software. Even so most of the special purpose FE-codes like DEFORM™ provide a certain material database, the quality and limits of validity have to be proven very carefully before usage. Especially for superalloys most companies simulating thermomechanical processes prefer to develop their own databases, thus their processes are covered in the most reliable way.

Whereas the measurement of elastic and thermal parameters, like Young's modulus and heat capacity, is defined in some specifications and delivers therefore quite reliable data, the measurement of flow stresses and interfacial properties like friction and heat transfer is strongly dependent on the experience of the engineer, who performs and evaluates the experiments. Temperature, strain rate and strain dependent flow stresses may be measured in compression, tension or torsion tests and have to be corrected mathematically to describe isothermal uniaxial

deformation processes. This data can be further fitted to one of the typical more or less empirical functions like the power law [7] or Hensel & Spittel law [8] which are implemented in the software or have to be programmed in a separate user routine. For nickel base superalloys low stacking fault energies, high amounts of alloying elements and several phases present during deformation are typical and therefore complex hardening and softening processes in dependence of temperature, strain rate and strain occur, thus the use of flow stresses in tabular manner combined with an interpolation in-between the measured values is most suitable.

In case of strong textures and therefore anisotropic behavior of the material additional focus has to be set on the yield function. While for hot die forging simulations in most cases a von Mises yield function [9] is sufficient, for cold or sheet forming operations a more dimensional criterion like for instance suggested by Hill [10] leads to more reasonable results.

The importance of accurate data for contact boundary conditions including heat transfer and friction are often underestimated. Most likely this is due to the complexity of the evaluation process [e.g. 11]. If all other data can be assumed accurate, it is possible to find reasonable friction and heat transfer data easiest by comparing the shape of trial forgings e.g. pancakes with the output of several simulation iterations. This approach is valuable for most superalloy forging processes, due to the fact that a certain allowance is anyway necessary. For friction it is additionally important to use the friction law, which is suitable for the simulated process, e.g. shear model for hot die forging.

### Improvement of Dimensional Quality

In most forging companies the finite element method is at least used to improve or even guarantee the dimensional quality of the final part. The two main failures, which designers want to avoid, are incomplete filling of dies as well as folds. If the basic requirements discussed above are fulfilled, insufficient filling may be detected directly in the final mesh, see Figure 3 a. Even so the FE software DEFORM™ is capable to highlight folds in the mesh, a closer analysis of each simulated step using the velocity arrows is absolutely necessary in order to prevent those folds, which may not be directly detected, as in Figure 3 b. Such a design must not result in a fold but can lead to a lack of material in the region marked with a circle. Anyway, the flash should be moved either to the bottom or top of the rib.

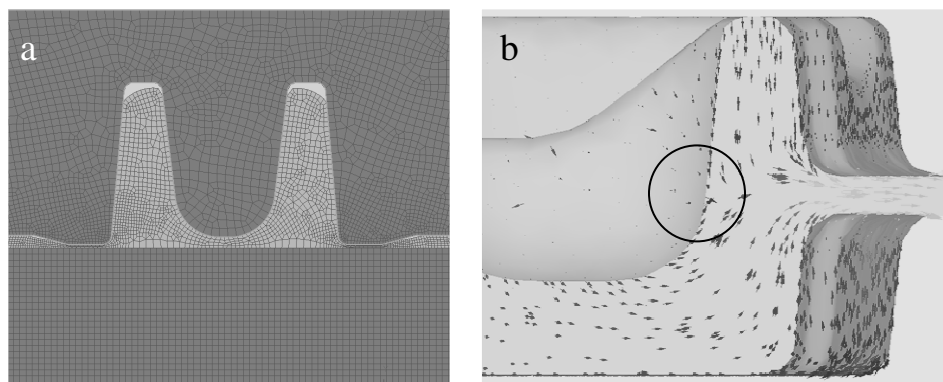


Figure 3: Finite element simulation showing a) insufficient die filling and b) probable folding due to material flow.

The geometrical stability of the dies has also a big impact on the dimensional quality of the final forging. This is notably critical if the forging is made of high flow stress materials like nickel base superalloys. High local stresses in the dies may result in plastic deformation or even in formation of cracks and die failure. To prevent such disastrous events a simulation of die stresses is useful. In most cases the assumption of a linear elastic behavior of the die material is suitable for the simulation of stresses in critical areas like small radii or deep cavities.



Figure 4: Elastic die stress analysis indicating plastic deformation in most areas of the edge radii.

If the elastic stress shows values higher than the yield strength of the die material a plastic deformation is most likely (Figure 4). As the amount of elements describing small radii has a significant influence on the result of the simulation, special emphasis has to be put on mesh generation. In order to guarantee a good comparability it is recommendable to use a similar number of elements per edge radius of interest for every die stress simulation.

#### Effect of Residual Stresses on Dimensional Quality

For most thermomechanical processes the temperature gradients during final cooling of the forging may result in residual stresses in the part. Dependent on the initial temperature differences, due to adiabatic heating and die chill, part geometry, cooling rate and microstructural changes a significant distortion during cooling and subsequent machining processes may result in a dimensional non conforming final part. The prediction of residual stresses using FE simulation requires an elasto-plastic material description, which increases complexity of the model and therefore decreases the probability of an easy convergence of the simulation. Again material data like low strain rate flow curves and elastic temperature dependent material data as well as an accurate description of heat transfer during cooling process are the key factors for a prediction of residual stresses.

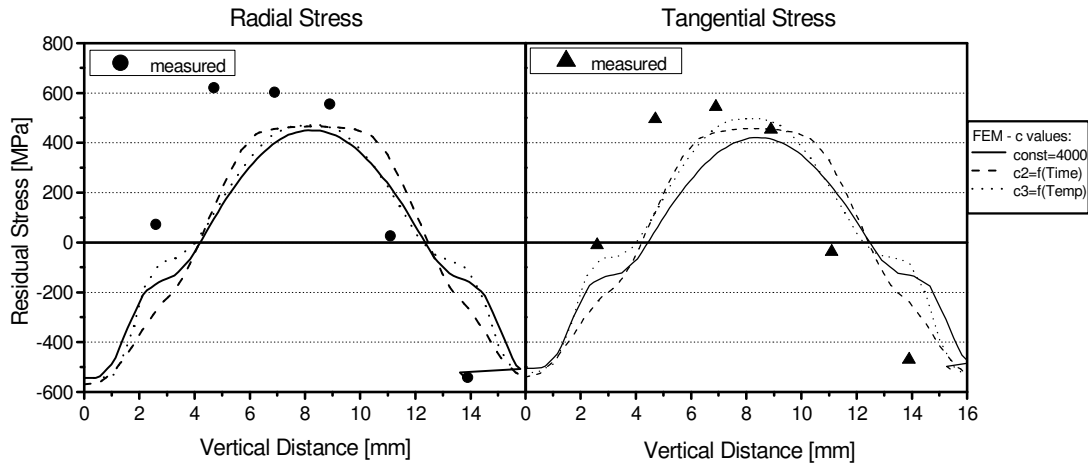


Figure 5: Simulated residual stresses, (left) radial and (right) tangential direction along the cross section of the axisymmetric part shown in Figure 7. The symbols indicate the stress values determined by neutron diffraction. [12, 13]

Figure 5 shows a comparison between FE-simulations of a water quenching process of an axisymmetric part made of alloy 718 using a constant heat transfer coefficient of 4000 W/m<sup>2</sup>K as well as heat transfer coefficients varying with time or with temperature respectively, and neutron diffraction measurement [12, 13]. Considering the measurement error of neutron diffraction of approximately  $\pm 50$  MPa and the simplification of an axisymmetric model including a stepped change of the heat transfer coefficient to describe the change of cooling media the accuracy of the model is highly satisfying.

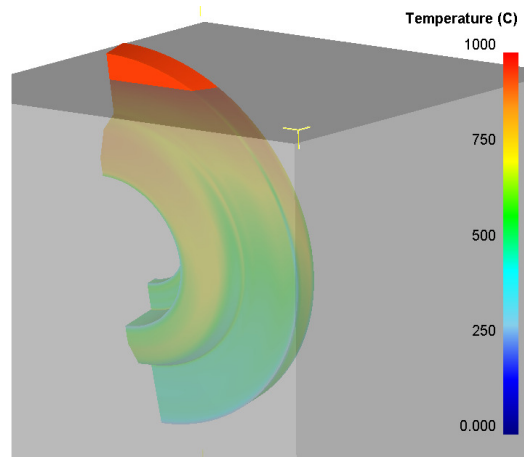


Figure 6: Simulation of a water quenching process including time dependent immersion in the liquid media.

An increase in accuracy is possible if the simulation is done in 3D including the time dependent immersion of the part in the cooling media (Figure 6). Though the convergence of such a

problem is much weaker than the simplified 2D model the simulation time effort for the same amount of elements in a cross section is in most cases uneconomical.

The easiest way to simulate the distortion during subsequent machining steps is to interpolate the residual stress state of the forging on the geometry of the final part, this results in a disequilibrium of the stress state and hence in a distortion. A higher accuracy can be achieved if the initial mesh is manually generated, thus material removal can be simulated by deleting a layer of elements (Figure 7). Therefore an interpolation of the stress data on a new mesh is not necessary.

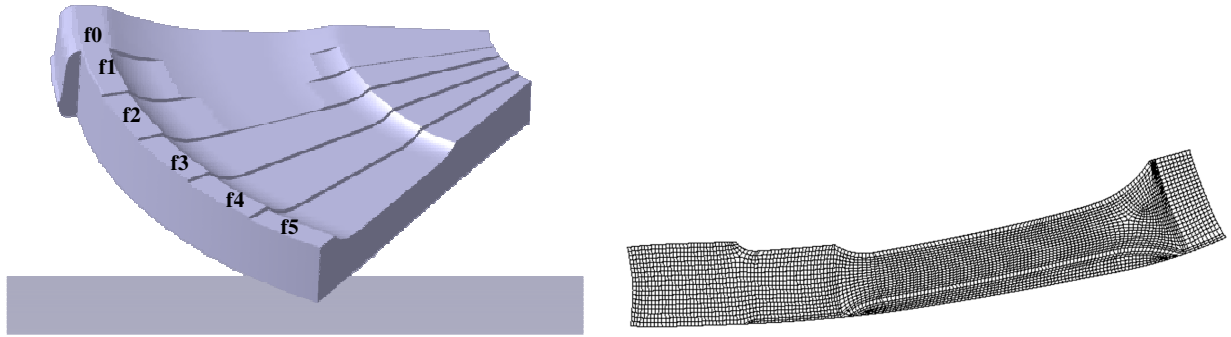


Figure 7: Simulation of the distortion after 5 machining operations (50x exaggerated) [14].

If the measured final distortion of a machined part and the simulated one show equivalent results an accurate simulation of the residual stress state in the forging can be assumed. In Figure 8 the distortion measurement of a 5 step turning trial of a forged and water quenched alloy 718 disc, illustrated in Figure 7, is compared with the distortion indicated by the DEFORM2D™ elasto-plastic simulation. The displacement along the disc radius shows good agreement between experiment and simulation for all machining steps. Therefore machining trials together with dimensional measurement offer an indirect method to verify residual stresses in forgings, with the additional advantage of an easier access and less costs compared to neutron diffraction method. Well known additional methods to verify residual stresses are the hole drilling method, x-ray diffraction, magnetic, electric and ultrasonic methods which are all capable to measure stresses only close to surface [15]

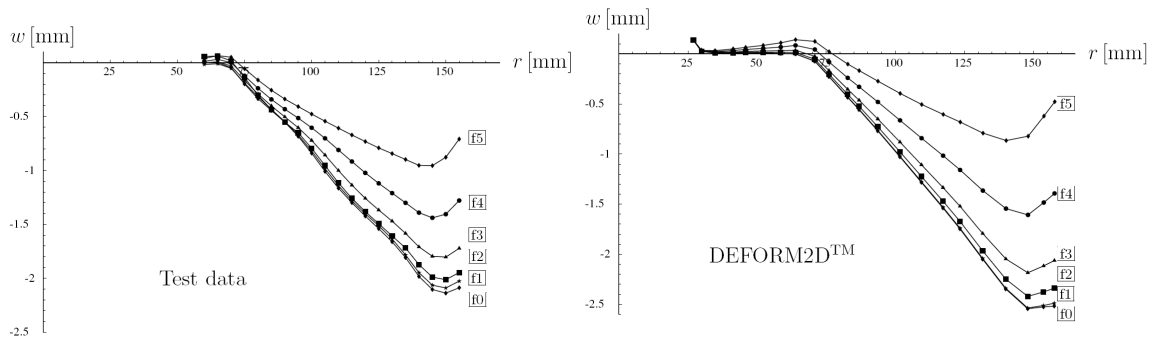


Figure 8: Distortion measurement and simulation of a forged and water quenched alloy 718 disc (see Figure 7) -  $w$  indicating deflection and  $r$  the radial coordinate on the disc.



## Microstructure Modeling to Optimize Forging Processes

The production of geometrically correct parts should be possible considering the above mentioned guidelines. Obviously this may not result in a forging fulfilling all metallurgical and mechanical requirements. Especially for nickel base superalloys a small variation in temperature and amount of deformation may result in a significant change of the microstructure. Skilled engineers are capable to design thermomechanical treatments within the limits of the alloy using processing maps as published in [16]. The success of this approach is not only dependent on the know how of the engineer but also on the number of forging and reheating operations as well as the complexity of the alloy. The number of influencing parameters may therefore exceed the imagination of a human mind and result in an increase of necessary forging trials. In recent years due to the increase in computer power the development of finite element coupled microstructure modeling has become more and more popular. The simulation of microstructural changes during thermomechanical treatments implies the mathematical description of process relevant physical phenomenons such as grain growth and recrystallization. In order to model these physical processes a classification of the different phenomenons is necessary and commonly used [17, 18]. The time and deformation conditions of nucleation and growth of recrystallized grains are parameters to distinguish the different recrystallization processes from each other. Dynamic recrystallization is therefore defined as the process where nucleation and growth of the nuclei happen during deformation. If the nucleation took place during the deformation and the growth subsequently without further deformation, the recrystallization is called meta-dynamic or post-dynamic. The third kind of recrystallization is static, which is well known where both nucleation and growth happen after the deformation during an annealing process. Whereas dynamic and meta-dynamic recrystallization generally lead to a refinement of the microstructure in alloys like 718, static recrystallization may result in local coarsening. [21]

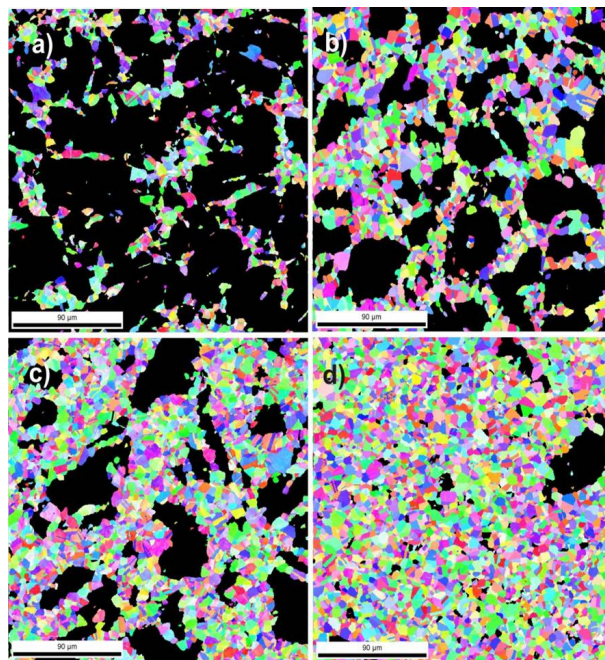




Figure 9: Progress of dynamic recrystallization at a temperature of 1000°C and a strain rate of 1/s at strains of 0.4 (a), 0.6 (b), 0.9 (c) and 1.6 (d) based on EBSD analysis [23].

In order to calculate microstructural changes due to these physical phenomena with the finite element method semi-empirical models with a set of material dependent parameters are commonly coupled to standard FE codes like DEFORM™. The necessary material parameters have to be derived from experiments like heat treatment trials, constant strain rate compression or tensile test and quantitative microstructure analysis as illustrated in Figure 9. [e.g. 19, 20, 21] The main advantages of such semi-empirical models compared to more physical based ones [e.g. 22] is that they usually converge very well within their limits and do not slow down the FE simulation significantly. A verification of such a microstructure model coupled with the FE code DEFORM2D™ is shown in Figure 10, indicating an isoline plot of the ASTM grainsize.

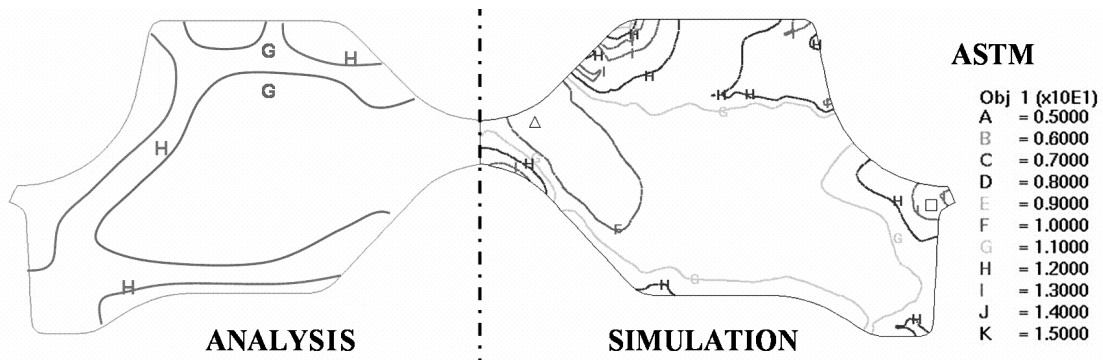


Figure 10: Comparison of simulation and microstructure analysis on a forged alloy 718 part.

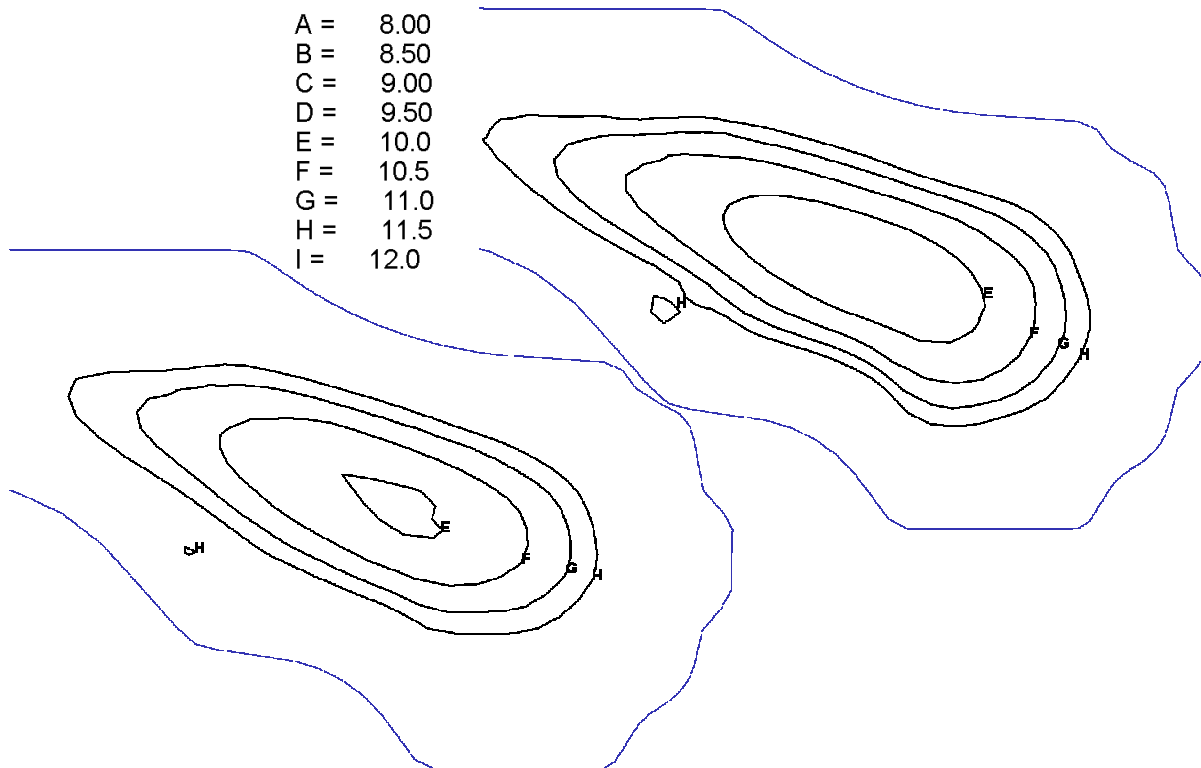


Figure 11: Difference in ASTM grainsize in an axisymmetric alloy 718 part where the blows in the final pressing operation are varied by < 2.5% in die stroke.

It is also possible to test the robustness of a forging process by simulating possible variations. Figure 11 shows that a small process variation in an alloy 718 disc forging may result in half an ASTM grainsize difference in the final part, which may be enough to lower the desired mechanical properties beneath the requirements.

In order to close the gap between grainsize simulation and prediction of mechanical properties of a superalloy forging the simulation of nanostructural changes, like the precipitation of  $\gamma'$  particles, is necessary. One possibility is to use the classical nucleation theory extended for multi-component systems [24, 25] implemented in a thermo-kinetic simulation software like MatCalc [26]. Assuming the availability of a proper thermodynamic and diffusion database covering all chemical elements of the alloy a simulation of dissolution and precipitation of different phases is possible. Figure 12 shows the results of several isothermal thermo-kinetic simulations and some experimental data of alloy Allvac®718Plus™ in a time temperature precipitation plot. More details regarding the method as well as further results of precipitation simulations of superalloys are presented in [28].

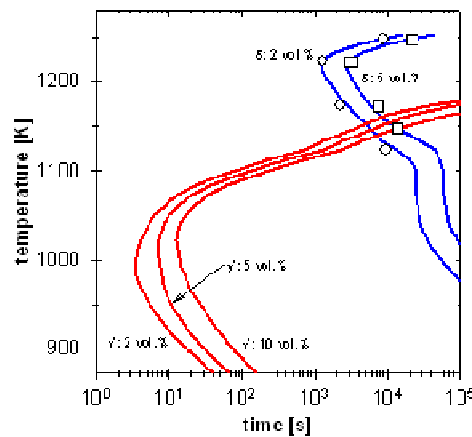


Figure 12: Isothermal time temperature precipitation (TTP) plot for the superalloy Allvac®718Plus™ calculated by thermo-kinetic simulations. Experimental data points indicate 2 vol.% (circles) and 5 vol.% (squares) of the  $\delta$  phase. [27]

A coupling of these methods with finite element simulation of forging processes is possible but would result in not acceptable simulation times. Therefore, such simulations are usually performed for time-temperature histories of some characteristic points in the forging only.

### Simulation of Fatigue Properties in Superalloy Forgings

A consequential next step is the attempt to predict mechanical properties, e.g. the fatigue life, of forged parts. This offers the possibility to design the part as well as the production process more purposefully and potentially decrease both cost and weight of the final part. Microstructural inhomogeneities, for instance coarser grains and textures, influence the fatigue properties in superalloy forgings. As mentioned above microstructure simulation predictions can be linked

with fatigue models [29]. Comparing the lifetime behavior of four different parts regarding to the evaluated microstructure, the maximum sustainable stress is reached by the specimen S/N-curve of part C with highest  $e$  and lowest  $b$ , followed by part B, see Figure 13. Comparing the microstructural damage parameters across the four forged parts, the values for part C report the most unimodal and fine grained microstructure. Evaluating the microstructure of part D, an increase of microstructural bimodality was detected (high  $b$ , low  $e$ ), which results in a reduced fatigue life. The microstructural parameters of specimens taken from part A show a huge statistical spread. The same characteristic was found on the distribution of sustainable load cycles. Additionally, it has to be taken into account that the specimens truncated from the parts were tested at different temperatures. The microstructural evaluation model is currently refined in order to respond the life-time behavior of alloy 718 at higher temperatures more accurately on the one hand and to more consistently link the DEFORM<sup>TM</sup> microstructure simulation with the fatigue simulation on the other hand, see [30].

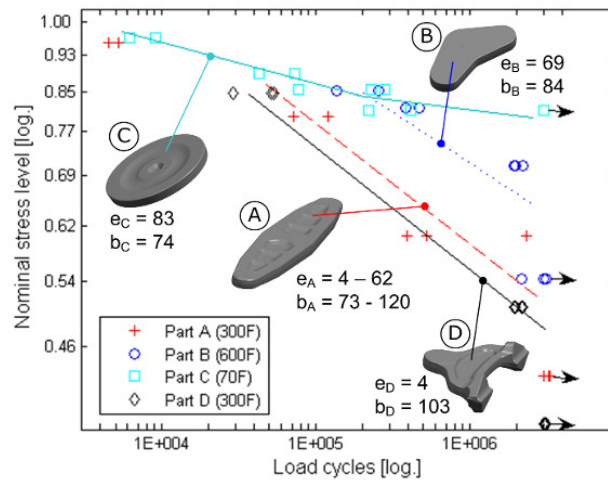


Figure 13: Lifetime-dependency of forged alloy 718 parts using microstructural based damage parameters  $e$  (microstructural energy parameter) and  $b$  (factor of heterogeneity) according to [29].

In order to use this information for a life-time prediction of final machined parts influences like notches, operation temperature and mean stress [e.g. 30, 31] as well as surface quality, residual stresses and type of loading have to be considered additionally. In a further step, the finite element code is linked to an optimization tool for determining the optimum set of manufacturing process parameters such that the component lifetime is maximized while taking process constraints into consideration [32]. Thus, to use this approach effectively co-operations along the supply chain are absolutely necessary, see Figure 14.

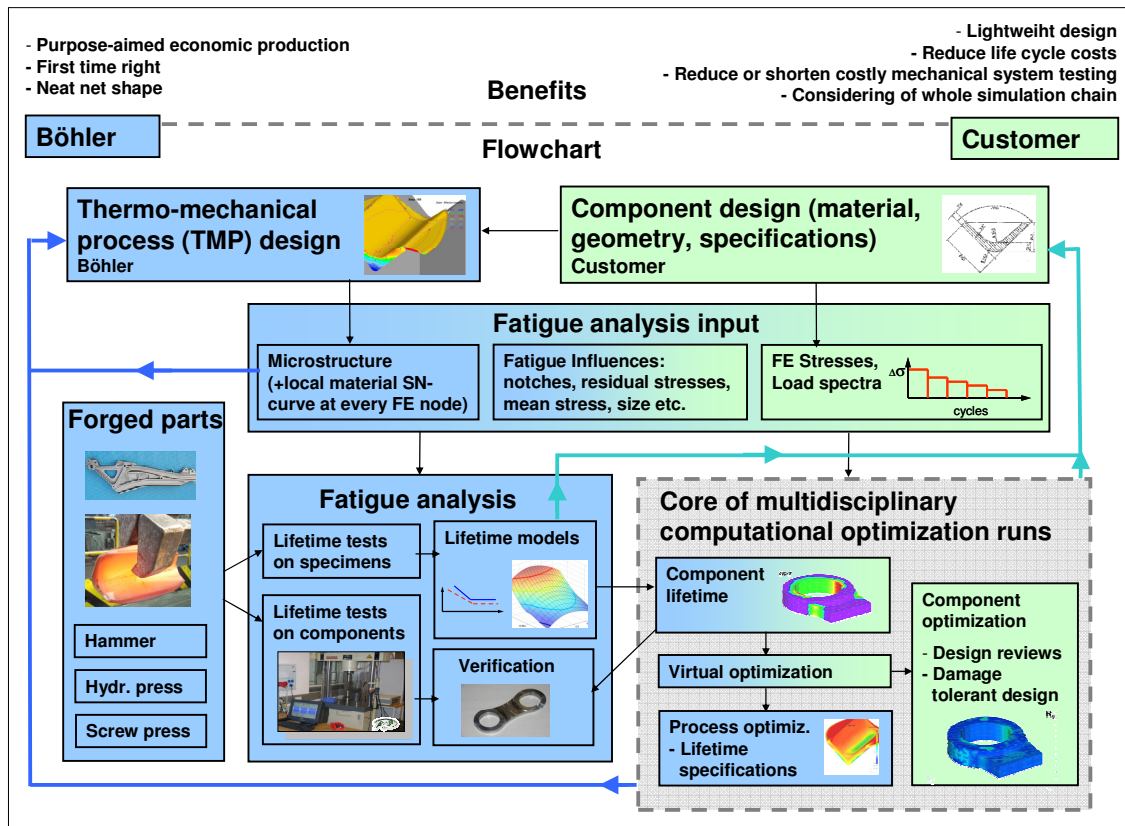


Figure 14: Co-operations along the supply chain for a purpose-aimed component and forging process design optimization.

## Conclusion and Outlook

The fast development of computational power as well as the usability of commercial finite element codes offer today the possibility to improve the product quality in a broad spectrum of industrial applications. Especially for superalloy forgings, which are mainly used for critical aircraft parts, product quality as well as production cost are natural drivers to secure the production processes by utilizing simulation techniques. Even so residual stress and microstructure simulations are available and used quite frequently, further improvement in order to predict mechanical properties is necessary in future. For instance the consideration of probabilities of impurities, segregation or coarse grains, etc. in the part and their influences on the final properties would be a valuable extension for microstructure and life-time models.

If the simulation is to be used in the most effective way in future, a strong focus has to be set on linking the simulation along the supply chain. Therefore special emphasis has to be put on the definition of interfaces between the simulation methods and scales on the one hand, but on the other hand also between customer and supplier. For simulations across different companies specifications for the exchanged data with regard to quality and validity as well as their format have to be defined carefully, in order to exclude misinterpretations. Even so the first steps have been done in this direction especially in the automotive industry the way towards a real “simulation chain” is still a long but nevertheless promising one.

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